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NUCLEON BOMBARDED GERMANIUM SEMICONDUCTORS, II

by

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The electrical behavior (conductivity, thermoelectric power, etc.) of germanium semiconductors can be described quantitatively once the number of carriers is known. The number of electrons (N-type conduction) or the number of holes (P-type conduction), depending on the type and number of impurities present, can be determined from Hall effect measurements. It is assumed (and made plausible by experiment) that each impurity atom releases one carrier.

It has been shown that the resistivity is due to:

(a) the scattering of electrons or holes by the lattice, given by the equation

$$\rho_L = DRT^{3/2}$$

where D is an experimental constant, R is the Hall coefficient = $\frac{7.37 \times 10^{18}}{n}$ and T is the absolute temperature in degrees Kelvin, and

(b) the scattering by singly ionized impurity centers given by the equation

$$\rho_i = A\ 1/(KT)^{3/2}\ \ln\ (1 + \alpha^2\ (kT)^2 d^2)$$

where A and α are constants characteristic of the semiconductor and d is one-half the distance between impurity centers or $\frac{1}{2}\sqrt[3]{n}$. No attempt was made to account for the possibility of scattering due to grain boundaries or due to existing lattice vacancies. Both effects must exist and seem to be responsible for the low temperature behavior of thin Te films. However, the agreement between experimental and theoretical curves in the case of Ge, Si, and Te ingots seems to indicate that these effects are not of primary importance in these materials.

Last fall experiments were started in the Purdue Laboratories to produce semiconductors by nuclear bombardment. Deuterons (~ 10 Mev), alpha particles (~ 20 Mev) and Be-D neutrons were used. The results* indicated that the impurities formed by nuclear transformations were too small by a factor of ~ 100 to account for the observed effects. The effect of a hydrogen-alloy was eliminated by carrying out similar experiments on thick samples and samples thin enough to allow full penetration of the deuterons. Since similar results were obtained in both cases, the displacement of lattice atoms must be responsible for the observed changes in the electrical behavior. Each displacement produces a lattice vacancy and an interstitial atom. The vacancy produces a perturbation of potential more effective than that produced by the displaced atom and should act as an acceptor of electrons.

In agreement with these expectations it was found that:

1) High-resistance inhomogenous material shows a marked decrease in resistance when bombarded. Apparently the introduction of a large number of lattice vacancies diminishes the inhomogeneity of the original material caused by fluctuation in impurity content.

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*K. Lark-Horovitz and associates, Bull. Am. Phys. Soc. (January 1948).

2) N-type germanium becomes converted to P-type material. This was shown by making Hall effect measurements on the material before and after bombardment.

3) P-N type barriers similar to the naturally sporadic occurring P-N type barriers, are formed by bombardment. These can be detected by their rectifying properties and their photoelectromotive forces.

The Hall effect measurements, together with the known α and d flux, indicate that approximately one new carrier is observed for one nucleon passing into the sample. Actual values range from .4 to 2.2 carriers/nucleon.

No measurable effect was found with the neutron flux from the Purdue cyclotron. Neither was there any permanent effect found due to bombardment with high speed electrons from an electron diffraction apparatus or from a 0.5 Mev Van de Graaff. If the interpretation of the experiments is correct. an effect with fast neutrons should be observable. The time required for an observable change with neutrons compared to the time required for an observable change with deuterons and alphas should compare with the corresponding inverse ratios of $\phi\sigma$.

Lark-Horovitz and Siegel exposed Ge samples in the Oak Ridge pile for ten minutes but no significant change in spreading resistance was observed. The samples were then exposed for 100 hours after this exposure. The measured resistivity had changed from ρ = 27.6 Ω cm to ρ = .14 Ω cm. These changes are found to be much more drastic than the ones observed after a few seconds bombardment with deuterons. The deuteron and alpha induced changes show a self-ordering effect as measured by changes in resistivity immediately after alpha bombardment. Only 7% of the neutron induced change in resistivity could be annealed out by heat treatment at 400°C during a period comparable with that given the deuteron and alpha bombarded samples. Prolonged heat treatment experiments are now under way to determine whether additional changes in resistivity will occur.

Two types of experiments have now been performed in the Oak Ridge pile.

1) Germanium samples selected and tested at Purdue for type of impurity, Hall coefficient, and resistivity have been exposed (a) in a hollow uranium slug to emphasize the fast neutron flux, and (b) in the graphite in the pile to emphasize the slow neutron flux. The resistance of the samples was measured continuously while in the pi'.:.

2) Commercial 1N38 rectifiers were exposed in similar positions in the pile and measurements on both forward and back resistance were made continuously. These measurements were made at about 1–4 volts, i.e., in a voltage range where spreading resistance and not the barrier determines the resistivity.

The N-type germanium, both high and low resistance samples, shows an initial marked increase in resistance which passes through a maximum and then steadily decreases upon continued irradiation. A high resistance P-type sample showed a monotonic decrease by a factor of 9 upon exposure to neutrons.

In the commercial Ge 1N38 rectifier, the forward resistance increases by a factor of approximately 100, reaches a maximum, and then decreases monotonically. The back resistance decreases steadily, eventually becoming equal to the forward resistance. Beyond this point the forward and back resistance decrease at the same rate.

A tentative explanation of these experiments may be given on the basis of the following considerations:

An impurity semiconductor conducts at room temperature or below due to carriers in the pass band (conduction or full band). If acceptors are added, the electron conductivity will be decreased if the electrons fill the new acceptor levels. This will continue until all the electrons are thus removed. This process leaves charged donators and acceptors in the lattice. If now additional acceptors are produced, the conduction electrons produced by thermal activation from the intrinsic level are also removed and hole conductivity alone will be observed. Since in germanium the effective mass of

holes is greater than the effective electron mass, the peak resistivity may be greater than the intrinsic resistivity expected.

The displacement of lattice points produces new scattering centers of two kinds, vacancies and displaced atoms. The continuous neutron bombardments over long periods also produce transmutations, thus leading to new impurity centers. The latter process, while negligible in the deuteron and alpha bombardment, introduces about 10^{-8} fractional atoms and for high purity samples this is not to be neglected in the resistivity range where primarily intrinsic carriers are produced and are responsible for conductivity.

The production of new scattering centers will introduce a new mean free path and only if this l_d (displacement m.f.p.) is much larger than l_L (lattice m.f.p.) or l_i (impurity m.f.p.), will its influence be negligible.

$$\frac{1}{l} = \frac{1}{l_L} + \frac{1}{l_i} + \frac{1}{l_d}$$

If the number of new carriers released is large as compared to the reduction of mean free path, the conductivity will increase ($\sigma = neb = n.e\, el/mv$) and this seems to happen in high resistance P-type sample; it is also in agreement with the behavior of the resistance of the back-direction in the 1N38 rectifier, which decreases upon neutron bombardment.

There are some indications that the large amount of γ radiation present in the pile may produce some photoconductivity, noticeable particularly in the range where the resistivity reaches a maximum.

Experiments to check this point, as well as comparisons between neutron and other nucleon exposure in the same sample, are under way now.

Preliminary experiments with Cu_2O, Si, Se, Te, etc., indicate a more complicated behavior than the germanium experiments. These may be due to chemical effects, which are negligible in the germanium alloys.

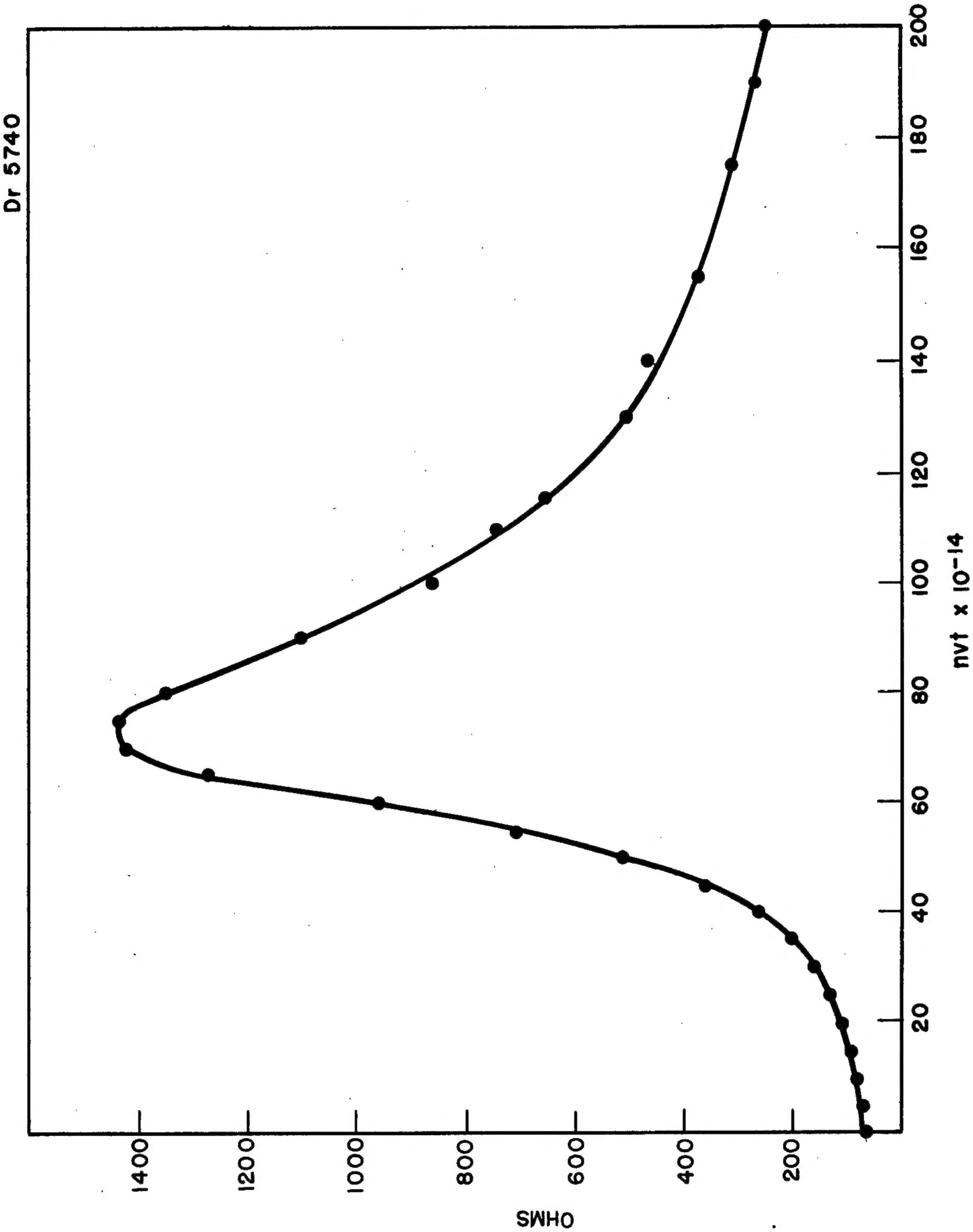

Figure 1. Resistance of high resistivity N-type germanium vs time of irradiation.

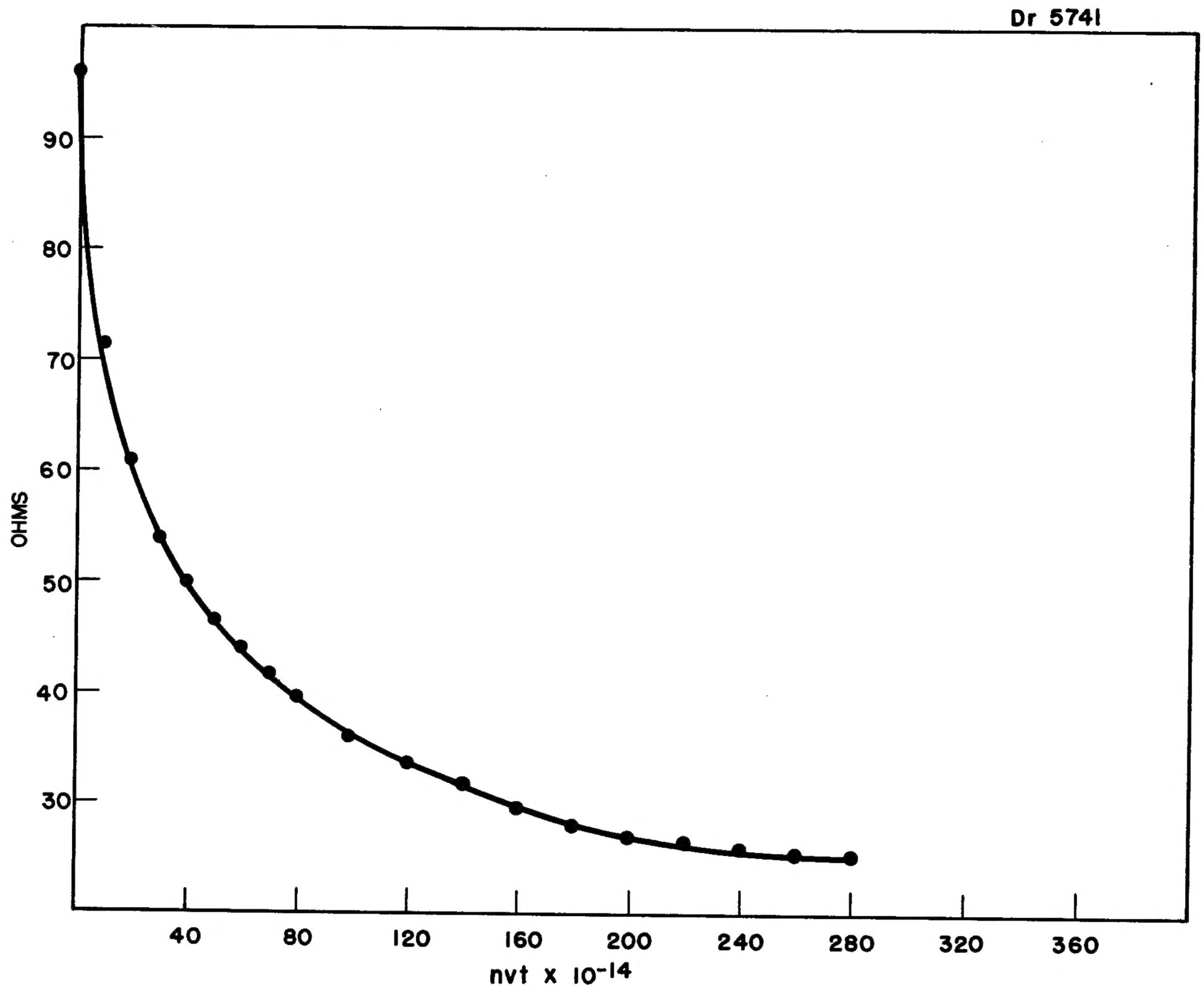

Figure 2. Resistance of high resistivity P-type germanium vs time of irradiation.

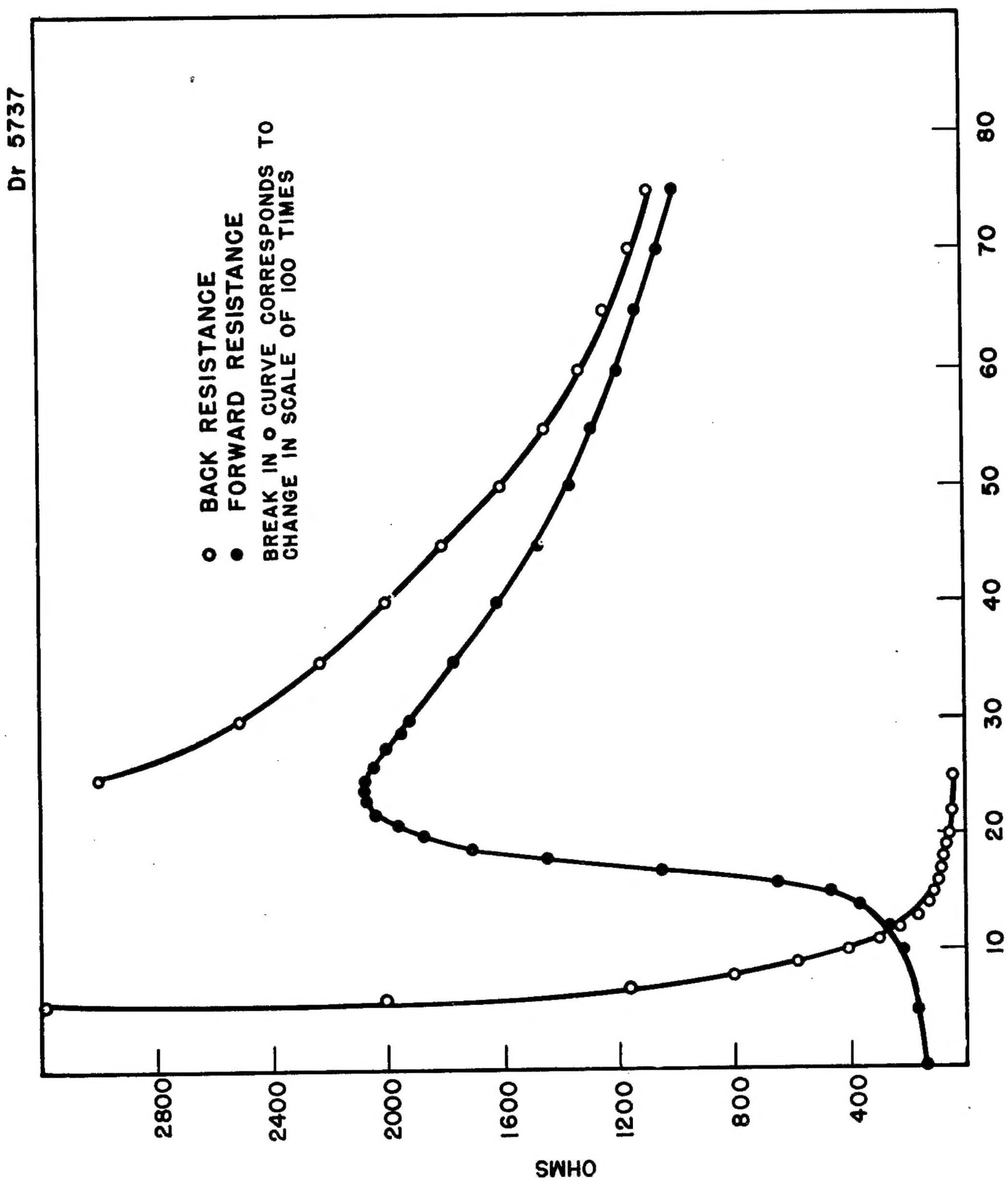

Figure 3. Resistance of IN38 rectifier vs time of irradiation.

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